SCA2003-17 : EXPERIMENTAL RESULTS FOR HIGH FLOW RATES OF OIL-WATER THROUGH HIGH PERMEABILITY MEDIA

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ABSTRACT

In some reservoirs, oil and water are produced at very high flow rate through zones of high permeability (super K). For this type of flows, inertial effects and formation of emulsion can limit the utility of standard models based on relative permeabilities. In order to study these effects, we have performed several series of experiments into two kinds of sand packs: water wet and of intermediate wettability (siliconate treatment). Velocities of oil and water were varied in a large range. Pressures were measured along the core and the average saturation were determined by weighting. The main results are the following:

1) inertial effects are observed for monophasic water flows, not for oil, due to its high viscosity (30 cp),
2) for all the velocities of oil and water, an emulsion with small oil droplets is produced;
3) using a standard approach to interpret the experiments leads to a single Kr curve for water but to a family of Kr curves of oil depending on velocities,
4) the effect of wettability on pressure drop is important, even if the capillary forces are negligible.

It has been written that 75% of reservoirs are producing oil and water on the form of emulsion. Our results show that flow of emulsion cannot be described by standard relative permeabilities. The small size of the observed emulsion is favorable to an homogeneous fluid approach. However, additional research concerning modeling of flow of emulsion in porous media should be performed in order to predict the effective viscosity.

INTRODUCTION

It has been published that 75 % of oil and water is produced in reservoirs on the form of emulsion [1]. The formation of emulsion results from the high flow rates in the vicinity of the well and also of a decrease of the interfacial tension caused by the presence of natural surfactants [2]. As a consequence of the effects of high flow rates and emulsion, the validity of standard models based on relative permeability may be questionable. In order to study these effects, we have performed several series of experiments into two sand packs of very high permeability equivalent to "super K" zones and without any. Velocities of oil and water were varied in a large range and the wettability of the medium has been modified. Even without surfactants, we have observed the formation of an emulsion at all the flow rates. Experiments were performed with two kinds of oil, Soltrol (viscosity 3 cp) and Marcol (30 cp). Results are similar and only Marcol experiments are reported in this paper.

We first present the experimental device, then the experimental results for different flow rates and the two kinds of sand packs (pressure drops, saturations and emulsion viscosity). Finally, we present the interpretation in term of relative permeabilities.

PROCEDURES

In this section, we present the experimental device and the procedures used to study oil-water two-phase flow in a porous media.

A schematic overview of the experimental device is presented in Fig. 1. It consisted in two volumetric pumps, a sand pack contained in a core-holder, and a separator. Several experiments were performed with different flow rates of water and oil which were injected separately through the sample held in a horizontal position. When a steady state is reached, the pressures and the average saturations were measured. The pressure drop was measured by a pressure transducer (Validyne) inside the core and the saturation in the sample was measured by weighting the core-holder after disconnecting all the tubings. At the end of each experiment, the oil-water mixture is separated by decantation in the separator.

At the outlet, the effective viscosity of the emulsion was characterized by measuring the pressure drop through a tube of known diameter (around 1cm).

Table 1. Physical properties (viscosity and density) of Marcol measured at 20°C.

	m (mPa.s)	r (kg.m^{-3})	$s_{water-oil}$ (mN.m^{-1})	$s_{air-oil}$ (mN.m^{-1})
Marcol 82	28.8	843	30.1	32.8

The core-holder is a stainless steel cylinder, 6 cm diameter and 35 cm long, filled with quartz sand of roughly 3 mm diameter. In order to study the effect of wettability, the quartz, which is naturally water wet, was made partially oil wet using a siliconate treatment [3, 4]. In the two cases, velocities of oil and water were varied in a large range. Physical properties of Marcol are presented in Table 1.

EXPERIMENTAL RESULTS

In this section we present the experimental results concerning the flow of the single-phases and the simultaneous flows of oil and water.

Single -phase Flow Results

In single phase flow, the pressure gradients as functions of superficial velocity are presented in Figs. 2 a,b for both water wet sand and treated sand. Results obtained with Marcol, which is nearly 30 times more viscous than water, show linear relationships between the pressure drop and the superficial velocity described by Darcy's law:

$$-\frac{\Delta P}{L}=\frac{m V}{k} \tag{1}$$

where ΔP is the pressure drop, L is the length of the core, m viscosity of the liquid, V is the superficial velocity (flow rate per unit section area) and k is the intrinsic permeability. Fitting the data with linear relationships leads to the values of the intrinsic permeability for each media which are presented in Table 2 a,b. The permeability for the water wet sand is slightly higher than the one obtained with the treated sand. A reduction of permeability is always observed in this kind of chemical treatment and may be due to the clogging of some pores by the polymerized siliconate.

The results obtained with water (Figs. 2 b) show quadratic relationships between the pressure drop and the superficial velocity. It is well known that this behavior is due to inertial effects which are not negligible compared to viscous effects at high flow rates. The Forchheimer equation is generally used to account for inertial effects:

$$-\frac{\Delta P}{L}=\frac{m V}{k}+\frac{r V^2}{h} \tag{2}$$

where r is the fluid density and h is called the passability factor. In petroleum engineering, we prefer to use the coefficient $b=1/h$ called the inertial factor or the non-Darcy flow coefficient.

Fitting the data by quadratic relationships leads to values of k and h presented in Table 2 for the different experiments. It can be seen that there are some discrepancies between the permeability that may be due to experimental accuracy.

Table 2a. Experimental values of permeability and passability (water wet sand).

	T **(°C)**	***k*** **(Darcy)**	***h*** **(m)**
Water	19	$4.56.10^{3}$	$8.30.10^{-05}$
Marcol	23	$5.03.10^{3}$	Not measured

Table 2c. . Experimental values of permeability and passability (treated sand).

	T **(°C)**	***k*** **(Darcy)**	***h*** **(m)**
Water	18	$3.37.10^{3}$	$5.83.10^{-05}$
Marcol	23	$3.64.10^{3}$	Not measured

Two-phase flow results

Observations at the outlet of the porous medium (before the capillary tube) show that oil and water flow simultaneously as a milky emulsion. From observation during decantation, it seems that the emulsion is formed of oil droplets into a continuous water phase. The type of emulsion and the size of the droplets was not characterized in this study but the milky aspect implies a size much smaller than the pore size. Since there is no surfactant, the emulsion is not stable and oil and water separate after a few minutes.

Measured pressure drops and water saturations are presented in Figs 3a,b,c and 4a,b,c as functions of water superficial velocity for different values of the oil superficial velocity. Although the capillary pressure is negligible compared to viscous effects, the main feature of these results is the strong effect of wettability on the pressure drop. Fig. 3c, shows the comparison of the pressure drops for the treated and not treated sands for the same oil superficial velocity. The main difference is the presence of a maximum at low water velocity for the non treated sand. Therefore, there are two domains:

- At low water superficial velocity, the pressure drop in the water wet sand is higher than the pressure drop in the treated.
- At high water superficial velocity, we observe the opposite behavior.

For saturation, the observed curve is similar to what is commonly observed for two-phase flow in porous medium for both sands. For a given constant oil superficial velocity, the water saturation increases when the water superficial velocity increases. In addition, as it is shown in Fig. 4c, the wettability of the medium has no effect on saturation.

Emulsion viscosity

The flow structure was characterized by measuring the pressure drop of the simultaneous flow of oil and water through the calibrated tube at the outlet of the sample. The "effective" emulsion viscosity is determined assuming that emulsion is flowing as a single-phase

Newtonian fluid at the superficial velocity of the mixture and that it follows Poiseuille's law. This is a very crude measurement that does not account for the effect of shear stress on the apparent viscosity. However, due to the low stability of the emulsion, it was impossible to use a rheometer to better characterize the rheology of the emulsion.

The results are presented in Fig. 5 for Marcol oil as function of the water volume fraction for the two kinds of sand packs. It can be seen that the wettability of the media has a strong effect on the effective viscosity of the emulsion. Values obtained with the water wet sand are always higher than those of the oil and water pure phases. On the other hand, the effective viscosity of the emulsion for the treated sand is lower than the viscosity of the pure oil phase.

Relative permeability curves

The approach commonly used to describe two-phase flow in porous media is based on the generalized Darcy's equations:

$$-\frac{\Delta P_w}{L} = \frac{m_w V_w}{k K r_w} \tag{3}$$

$$-\frac{\Delta P_o}{L} = \frac{m_o V_o}{k\, K r_o} \tag{4}$$

where w and o stand for water and oil respectively, P is the pressure (capillary pressure is neglected), L is the sample length, V is the superficial velocity, k is the intrinsic permeability, and Kr is the relative permeability.

For flows in porous media, it is well established that when inertial effects are negligible, the relative permeability of each fluid is a unique function of saturation. This is not the case in our experiments. The calculated Kr_w and Kr_o are presented in Figs. 6a,b as functions of measured water saturation. It can be seen that Kr_w is effectively only function of water saturation, while there are several curves of Kr_o depending on the oil superficial velocity for both treated and non-treated sands.

DISCUSSION

This set of experiments show two main physical mechanisms:

1) effect of wettability on pressure drop and viscosity and not on saturation
2) effect of flow rate on oil relative permeability

The effect of wettability on the properties of the emulsion has been observed and related to the emulsion morphology. Following Alvador [5], a water wet medium would lead to a continuous water phase (oil-in-water emulsion), while an oil wet medium would lead to a water-in-oil emulsion. However, in our experiments, the emulsion looks like an oil-in-water emulsion for both kinds of sand. Nevertheless, experimental measurements of the dynamic viscosity show clearly that there is a strong difference of the flow structure according to whether the sand is perfectly or partially water wet. More investigations are therefore needed in order to characterize more accurately the emulsion morphology.

For the effect of flow rate on oil relative permeability, the first explanation is related to inertial effects like for liquid-gas flow [6]. For similar flow rates, inertial effects are observed in pure water but not in oil which is much more viscous than water. However, in both kinds of sands, the effective viscosity of the emulsion is higher than water viscosity, and inertial effects may be negligible. In addition, the curves in Fig. 6a does not correspond to what is commonly observed with liquid-gas flow in porous media. In particular, models developed for liquid and gas flow are not appropriate to describe flow of emulsions through porous media [6]. The other explanation is related to the effective viscosity of emulsion which depends on the flow rate [7]. In order to model these flows, more experimental investigations are needed.

CONCLUSIONS

We have described several series of oil water injections into two kinds of sand packs of very permeability: water wet and of intermediate wettability (siliconate treatment). There was no added surfactant and velocities of oil and water were varied in a large range. Pressures were measured along the core and the average saturation were determined by weighting. The main results are the following:

- inertial effects are observed for monophasic water flows, not for oil, due to its high viscosity (30 cp).
- for all the velocities of oil and water, an emulsion is produced;
- using a standard approach to interpret the experiments leads to a single Kr curve for water but to a family of oil Kr curves, depending on velocities;
- the effect of wettability on pressure drop is important, even if the capillary forces are negligible.

Our results show that flow of emulsion cannot be described by standard relative permeabilities. The small size of the observed emulsion is favorable to an homogeneous fluid approach. However, additional research concerning modeling of flow of emulsion in porous media should be performed in order to predict the effective viscosity.

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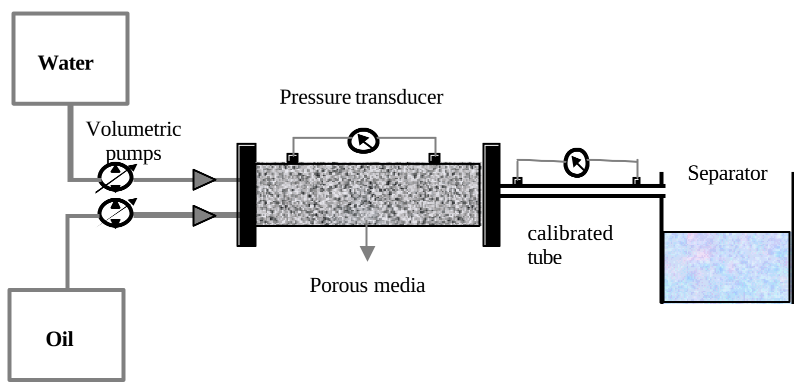

Fig. 1 - Schematic view of the experimental set-up.

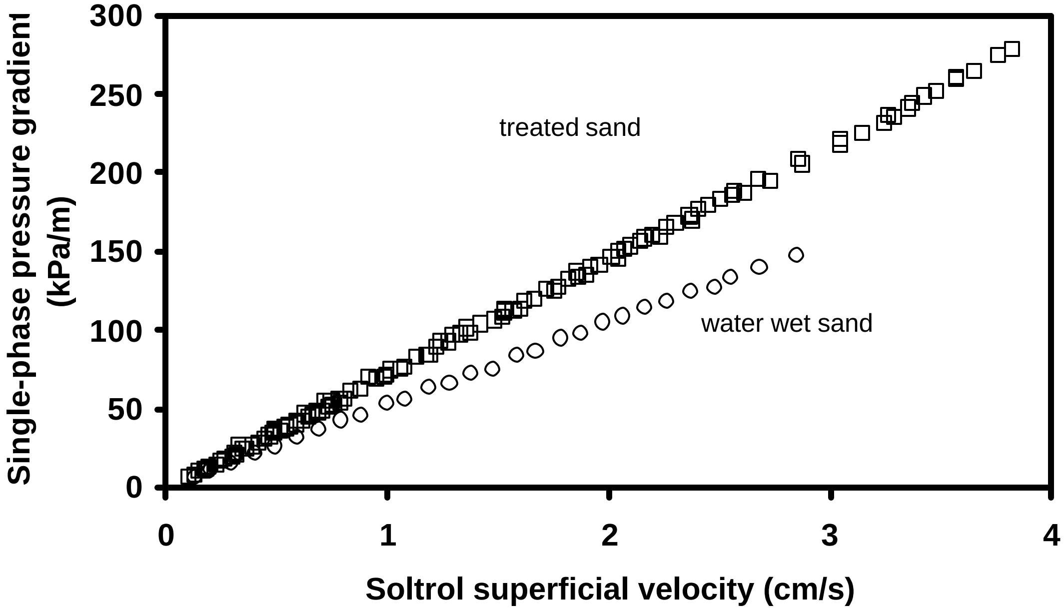

Fig. 2a - Pressure drop during Marcol single-phase flow.

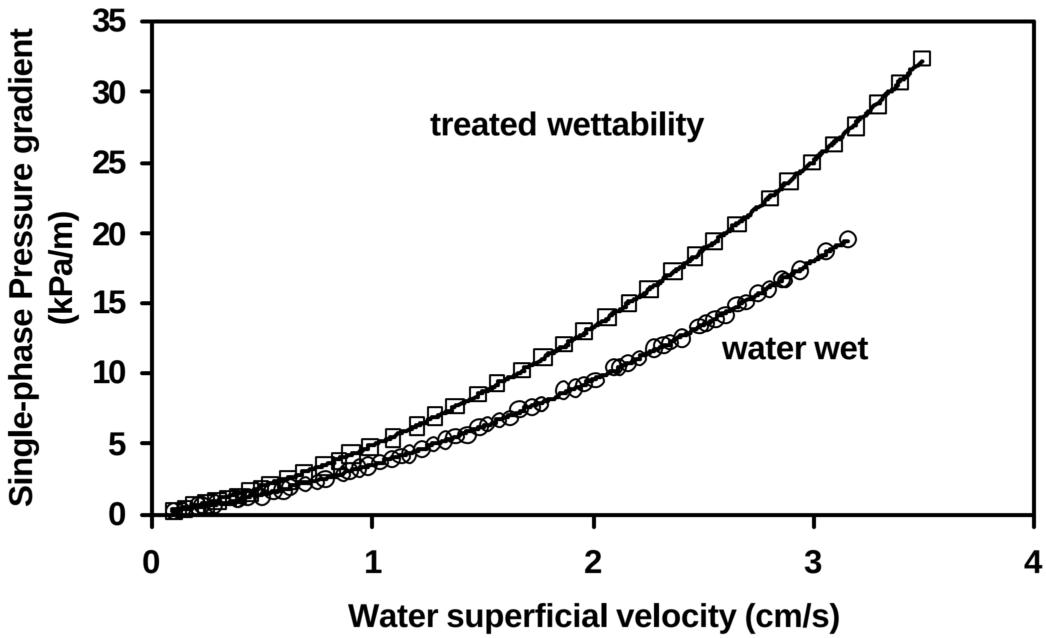

Fig. 2b - Pressure drop during water single-phase flow. The solid line represent the fit by the quadratic Forcheimer equation.

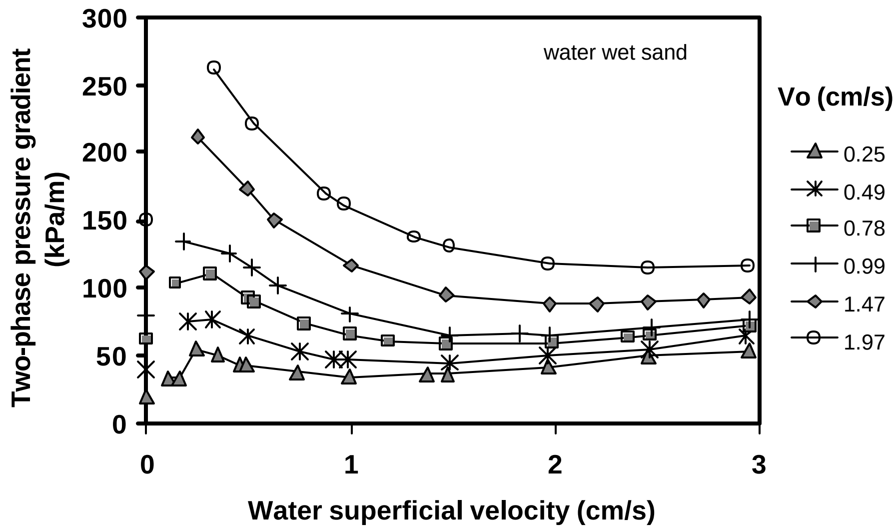

Fig. 3a - Pressure drop during two-phase flow. Experiments performed with the water wet sand.

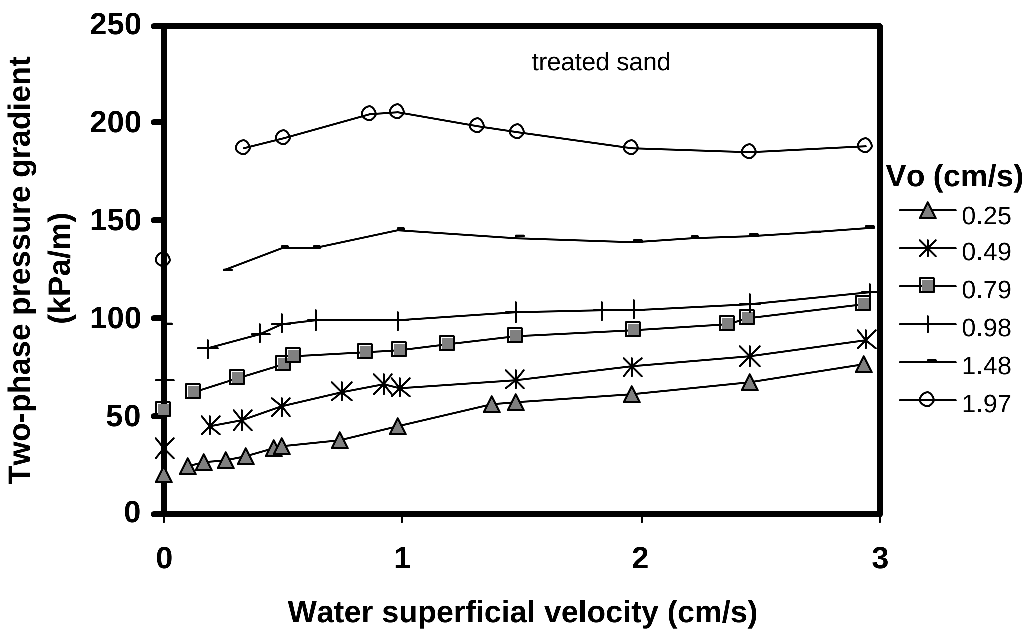

Fig. 3b - Pressure drop during two-phase flow. Experiments performed with the treated sand..

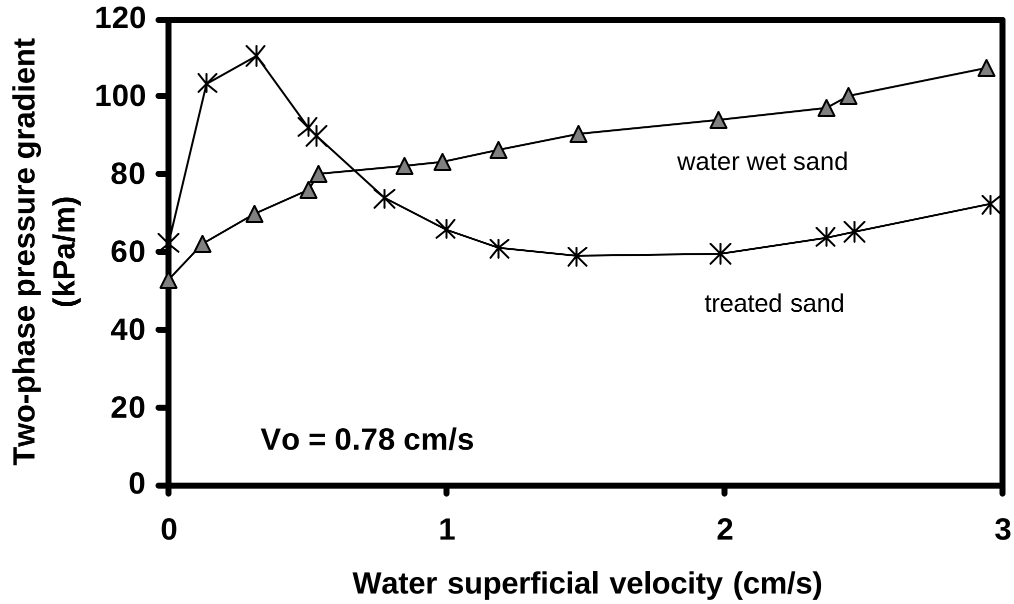

Fig. 3c - Pressure drop during two-phase flow. Comparison between two experiments performed at the same oil superficial velocity with treated and non-treated sand.

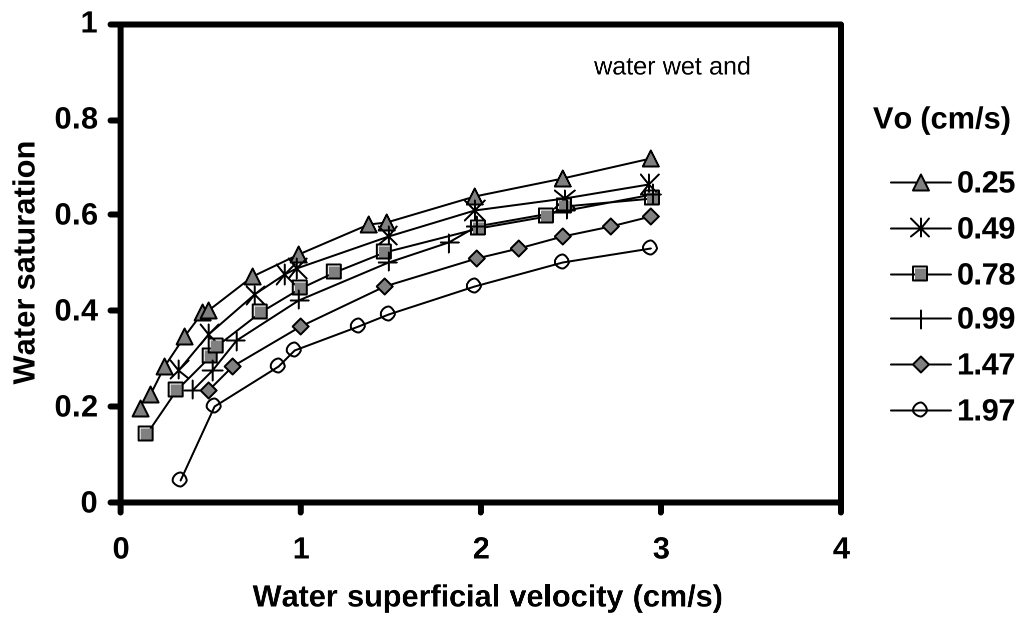

Fig. 4a - Water saturation for the water wet sand.

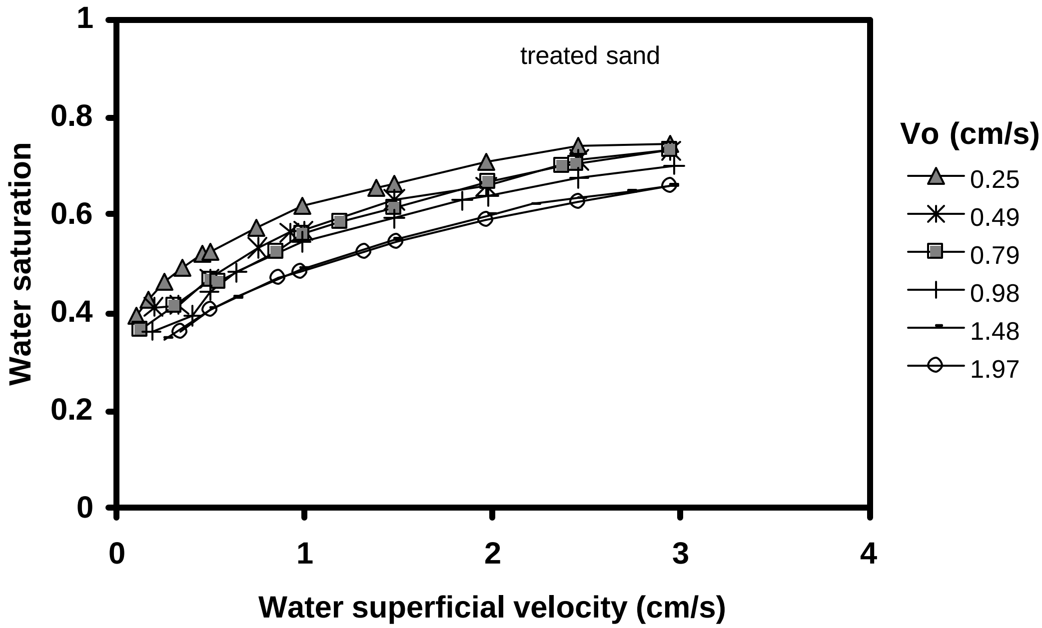

Fig. 4b - Water saturation for the treated sand.

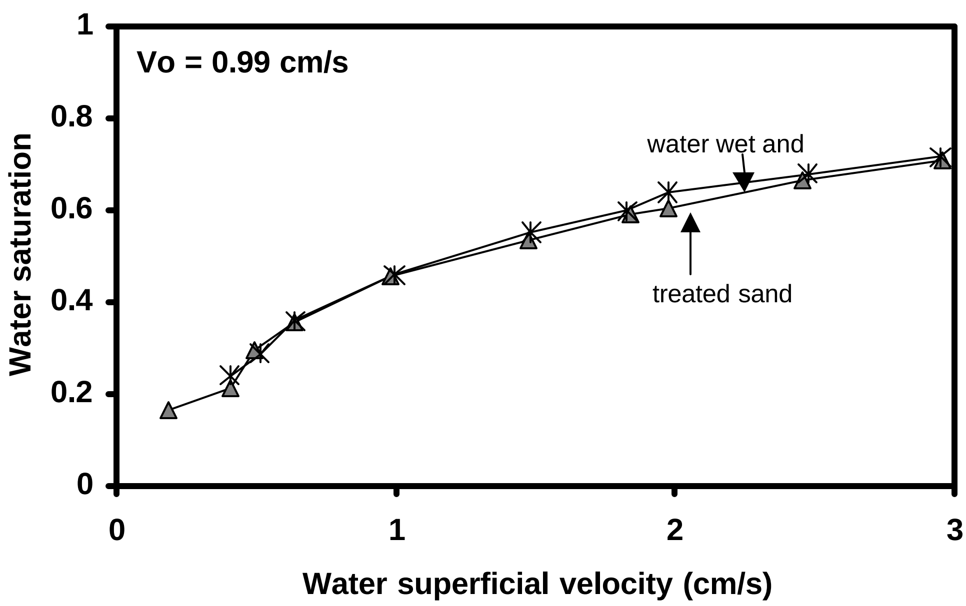

Fig. 4c - Water saturation. Comparison between two experiments performed at the same oil

velocity.

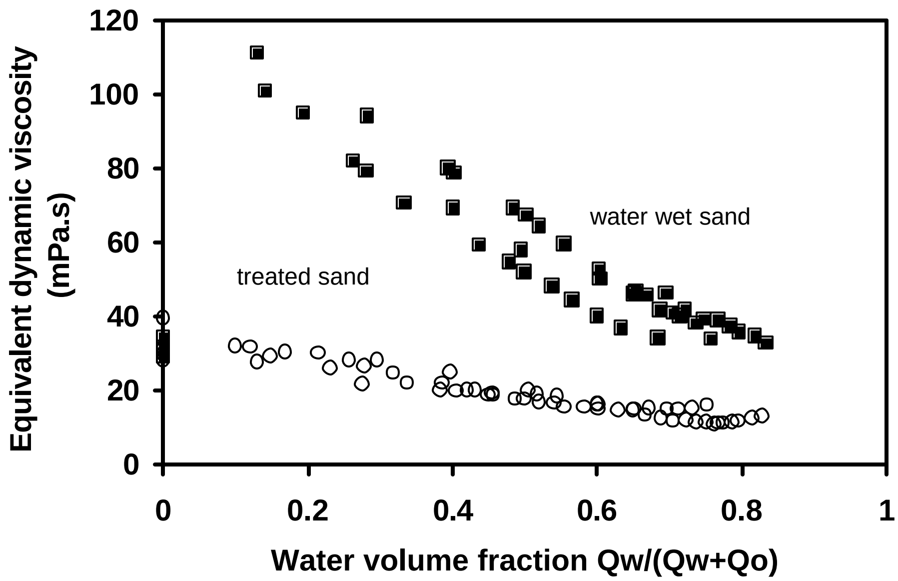

Fig. 5 - Effective viscosity of the emulsion at the outlet of the porous medium for treated and non-treated sands.

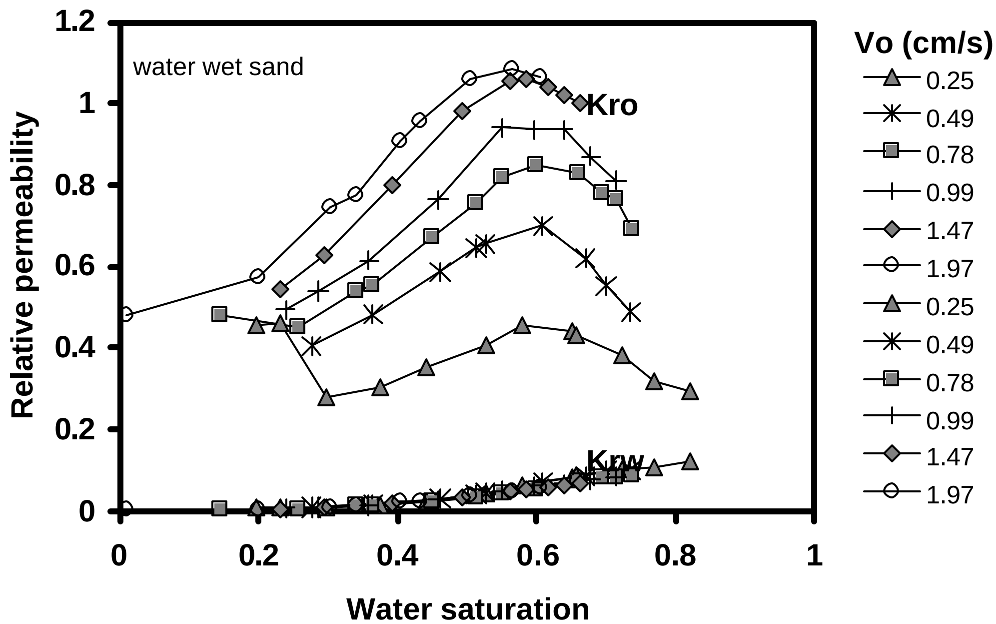

Fig. 6a - Oil and water relative permeabilities for the water wet sand.

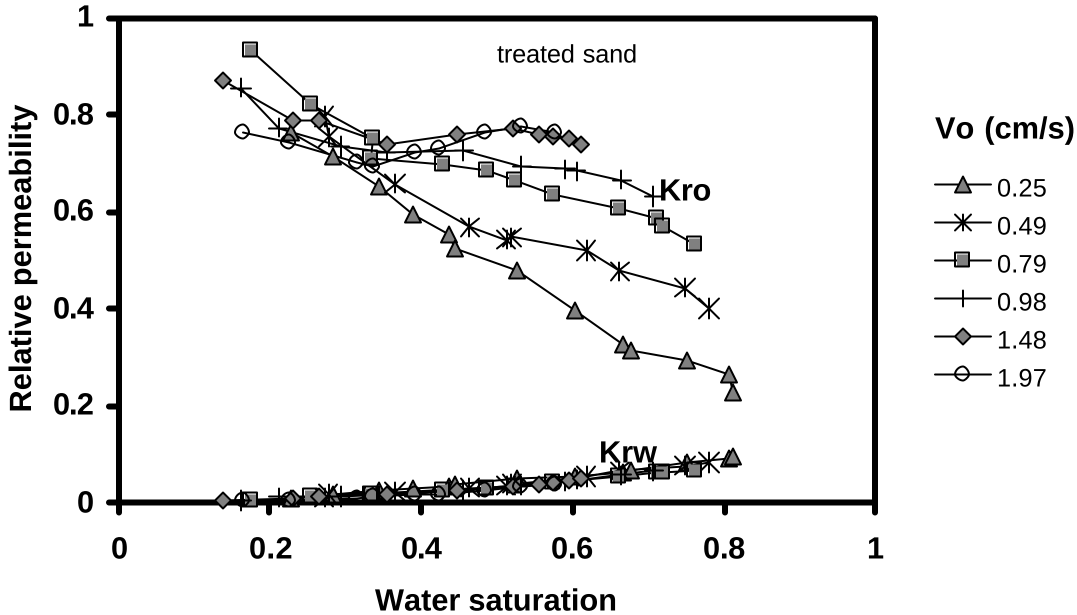

Fig. 6b - Oil and water relative permeabilities for the treated sand.